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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

hp	horsepower	V	volt
MB	megabyte	W	watt
Ω	ohm		

MOTOR MONITORING SYSTEM FOR A CONTINUOUS MINER

By John R. Thalimer,[1] John J. McClelland,[2] and Gerald T. Homce[3]

ABSTRACT

The U.S. Bureau of Mines has investigated the early detection of insulation failure in squirrel cage induction motors for the past 4 years. Research was done using a sophisticated empirical data-modeling technique based on values calculated from a motor's voltage and current phasors. This technique produces two polynomial equations that calculate the insulation leakage current and power. These models were implemented in a prototype system that monitors six motors on a continuous miner for insulation leakage. These insulation leakage values are used to anticipate insulation failure.

The system consists of a motor-data-system for each motor on the machine and a control computer located away from the miner. Each motor-data-system consists of an analog interface to the motor's voltages and currents, a single-board computer that reads digitized data and calculates voltage and current phasors, and a bus node that interfaces the single-board computer with the rest of the system by way of a serial bus system. Using this bus system, the control computer requests and receives phasor data from the motor-data-systems.

From these data the control computer calculates and displays two deterioration values for each motor, for leakage current and power, using Bureau-developed models. These values are stored in a data base from which the user can display graphs of each motor's deterioration values over time.

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INTRODUCTION

More than 50% of all industrial motor failures are due to winding insulation failure (*1*).[4] This, along with bearing failure, accounts for 80% of all failures. Therefore, combining conventional bearing failure detection methods with winding insulation failure detection methods will create a system that can detect up to 80% of all electric motor failures.

Prediction of motor failure is important from both a safety and a production standpoint (*2*); it is much safer and less expensive to change a motor before failure than during an operating shift.

Presently, insulation resistance (megger) testing of motor windings is done at some mine sites. For this test the motor must be taken out of service and disconnected from the power system.

The U.S. Bureau of Mines is conducting research to develop techniques to determine the leakage current and power due to deterioration of motor winding insulation. Research has shown that this leakage current and power can be determined by measuring the motor's voltage and current phasors while the motor is in normal operation. The leakage current and power are modeled as polynomial functions of common engineering values that can be calculated from these phasors. The Motor Monitoring System (MMS) is the first attempt at using this research in a prototype application.

The MMS is a computer-based distributed processor system for anticipating catastrophic insulation failure in the induction motors on a continuous miner. The system is being demonstrated on a Joy 16CM[5] continuous miner (fig. 1), which is used by Bureau researchers as a test-bed for advanced mining applications. This research addresses two Bureau goals: to provide a safe and healthful work environment for miners and to reduce the cost of coal production.

[4]Italic numbers in parentheses refer to items in the list of references at the end of this report.

[5]Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

Figure 1.—Continuous miner.

THEORETICAL BASIS FOR EARLY MOTOR FAILURE DETECTION

Past Bureau contract research examining mine electrical system safety investigated the possible benefits of using continuous monitoring techniques to evaluate the condition of power system components (*3*). Researchers concluded that early detection of deterioration in mine electrical system components could significantly improve system safety and availability. As part of an independent research program, the work was continued, with further analysis of the relationship between the mechanisms of electrical component deterioration and their resulting signatures (*4*). Recent Bureau-funded efforts in this area produced several computer models to simulate power system and induction motor operation under deteriorated conditions and identified characteristics associated with deterioration involving windings in induction motors (*2*).

The research programs just described produced information that can be used to form a theoretical basis for the detection of low-level insulation deterioration. However, this information had not yet been successfully implemented in a well-defined method to detect the presence and level of electrical deterioration. This situation prompted the Bureau to initiate an in-house research project to develop such a method.

APPROACH

Information from past research suggests that a mathematical relationship or group of relationships can be used to identify electrical deterioration, using measurable power system parameters, but identifying the appropriate input features and deriving suitable relationships is a complex task. In-house research utilized an empirical data mathematical modeling approach to this problem, employing commercially available data-modeling software and information from laboratory-generated power systems to create the necessary relationship(s).

PNETTR-4X (Polynomial NETwork TRainer version 4X) is a data-modeling software package marketed by General Research Corp. that can create a polynomial network model called an adaptive learning network (ALN) to represent a physical process (*5*). PNETTR uses an unsupervised learning method to build ALN's, selecting only the input features that are necessary for accurate modeling. For this research, input data were electrical features extracted from laboratory systems undergoing simulated deterioration. PNETTR selected the features that were most significant for modeling system operation and created ALN's, relating them to dependent variables indicating deterioration severity.

This research modeled three-phase squirrel cage induction motors, the electric motors most widely used in mining operations. Electrical failure often originates with the breakdown of insulation and subsequent leakage of current through an abnormal path, eventually resulting in a fault (*3*). The process of insulation breakdown was used in this research as the basis for quantifying progressive deterioration of induction motors, with deterioration severity indicated by the level of current flowing and power dissipated in an abnormal path. Such leakage current can seldom be located, much less measured, in the field, but it is readily controlled and measured in laboratory simulations. Therefore, laboratory simulations can be used to establish an empirical relationship between deterioration current and power levels and readily measured electrical values, and this relationship can be employed to detect deterioration in the field.

Motor-alternator sets powered by a motor test station and loaded by a bank of resistors were used to generate the required power system terminal information. To simulate varying levels of current leakage (insulation deterioration) across various points on the motor system, a bank of resistors was connected to the motor leads through a variable transformer. The leakage current levels simulated for laboratory tests were recorded during data acquisition for each sample taken and, along with the calculated deterioration power, became the dependent variables in PNETTR data files. Electrical parameters derived from three-phase voltage and current terminal values served as independent variables.

Laboratory-generated data represent a wide range of motor system operating conditions, including different deterioration (insulation leakage) positions and levels and different motor load levels. Several individual samples were taken for each distinct laboratory system condition and were subsequently processed to yield system observations for input to PNETTR. Most of these observations were used in the development of the ALN's, while the remainder were reserved to form independent evaluation data sets. The root-mean-square (RMS) of residuals between the actual and model-calculated deterioration levels for these evaluation data sets provides an indication of ALN accuracy.

FAILURE DETECTION ADAPTIVE LEARNING NETWORKS

Results of PNETTR modeling indicate that ALN's can detect and quantify low-level deterioration on a motor system, independent of deterioration type and level and motor load level. The most accurate ALN's developed thus far, covering a wide range of simulated system conditions for 50-, 100-, and 150-hp motors, are shown below.

Deterioration current ALN:

$$X_7 = A_1 + A_2X_1 + A_3X_5 + A_4X_1X_5 + A_5X_1^2 + A_6X_5^2 + A_7X_1^3 + A_8X_5^3,$$

and

$$Y_1 = A_9 + A_{10}X_7 + A_{11}X_2 + A_{12}X_3 + A_{13}X_2X_3 + A_{14}X_7^2 + A_{15}X_2^2 + A_{16}X_3^2 + A_{17}X_7^3 + A_{18}X_2^3.$$

Deterioration power ALN:

$$X_8 = A_{19} + A_{20}X_1 + A_{21}X_2 + A_{22}X_4 + A_{23}X_1X_2 + A_{24}X_1X_4 + A_{25}X_1^2 + A_{26}X_2^2 + A_{27}X_1^3 + A_{28}X_2^3,$$

and

$$Y_2 = A_{29} + A_{30}X_8 + A_{31}X_6 + A_{32}X_8X_6,$$

where X_1 = negative sequence current polar magnitude,

X_2 = negative sequence current polar angle,

X_3 = negative sequence current x-coordinate,

X_4 = negative sequence current y-coordinate,

X_5 = zero sequence current polar magnitude,

X_6 = three-phase average of real power,

X_7 = first-layer output for deterioration current ALN,

X_8 = first-layer output for deterioration power ALN,

Y_1 = deterioration current level,

Y_2 = deterioration power level,

and A_1-A_{32} = coefficients.

The RMS errors for calculation of deterioration power and current, using the above ALN's to evaluate independent data sets for each motor used in training, are listed in table 1.

Table 1.—Root-mean-square errors for calculation of deterioration current and power, percent

Adaptive learning network	50-hp data	100-hp data	150-hp data
Current	1.8	2.0	1.9
Power	1.3	1.5	1.4

Whether errors of several percent (of motor line current or power) are acceptable for actual deterioration-detection systems depends on the as-yet unconfirmed characteristics of induction motors prior to complete failure. Considering, however, that 25% leakage current levels can exist in motors without immediate obvious effects, the resolution possible with the ALN accuracies listed in table 1 may well be acceptable for practical deterioration monitoring (*4*).

In the subject research, failure detection techniques were developed using simulated deterioration conditions, based on the assumption that in actual motor failure, insulation degradation would be gradual and of sufficient magnitude to allow early detection. Field measurements from previous research suggest that this is the case, but no quantitative study has been done to verify the foregoing assumption.

To address this situation, ongoing work includes accelerated life testing of motors. These tests attempt to induce gradual insulation failure in laboratory motors to confirm the presence of detectable insulation breakdown prior to motor failure. In these tests, typical mine equipment motors are operated at above-normal temperatures to accelerate winding insulation degradation. Motor electrical parameters are closely monitored during this deterioration process, and deterioration current and power levels are calculated using ALN's. The results are analyzed to identify unique signatures present prior to complete motor failure. Carefully controlled acceleration of motor aging permits the completion of this work in a practical time frame, while allowing extrapolation of results to motor life under normal operating conditions.

Another approach for validation of ALN-based techniques to detect early motor failure is long-term testing of a large number of motors in the field. Currently proposed work would monitor 25 to 50 motors in a mineral processing plant over a period of several years. This would allow ALN analysis of motor characteristics prior to actual failures under normal operating conditions and, as described above, evaluate the ability of ALN's to anticipate complete failure.

HARDWARE DESCRIPTION

The MMS installed on the Joy 16CM continuous miner is a distributed processor system interconnected with BITBUS, a commercially available control bus system (fig. 2). Connections are made to BITBUS through nodes that are connection points on the bus. The control computer is the master node, which controls all operation on BITBUS, and the bus node portions of the motor-data-systems are slave nodes. The miner has a separate BITBUS network that is used for control and navigation. The MMS is designed to eventually link into the control and navigation network.

Except for the control computer, the system is mounted on the miner. Figure 3 shows a box containing most of the hardware mounted on top of the miner's left-side contactor case. Figure 4 shows the analog boards, single-board computers, and bus nodes mounted inside this box. Each motor's current and potential transformers are mounted inside the miner's contactor cases. The six motors range from 15 to 175 hp. Figure 5 shows the location of the MMS, motor controls, and motors.

The control computer is located away from the miner and is the control point for the monitoring system. It also calculates and stores motor deterioration data.

Each motor-data-system is interfaced to its motor through an analog interface and analog-to-digital converter (ADC). This ADC is integral to the single-board computer's microprocessor. On command from the control computer, the motor-data-system digitizes phase-to-phase voltage and line current analog signals, and from these values calculates phasor values using a fast Fourier transform. After the motor-data-system finishes the phasor calculations, they are sent to the control computer using BITBUS, for use in calculating deterioration values.

The motor-data-systems' bus nodes provide an interface between the motor-data-systems and BITBUS. These nodes are slave nodes that can only respond to commands sent from the master node. The master node is a board contained in the control computer.

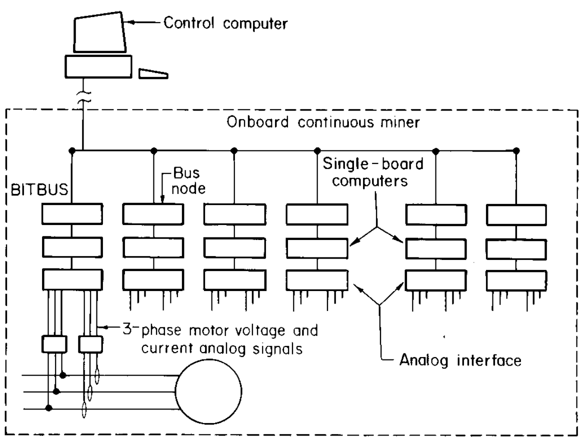

Figure 2.—Motor Monitoring System for continuous miner.

CONTROL COMPUTER

The control computer is an IBM Advanced Technology (AT) clone personal computer (PC) with a 40-MB hard disk. It is connected to the BITBUS through an Intel PCX344 Intelligent BITBUS interface board plugged into an expansion slot.

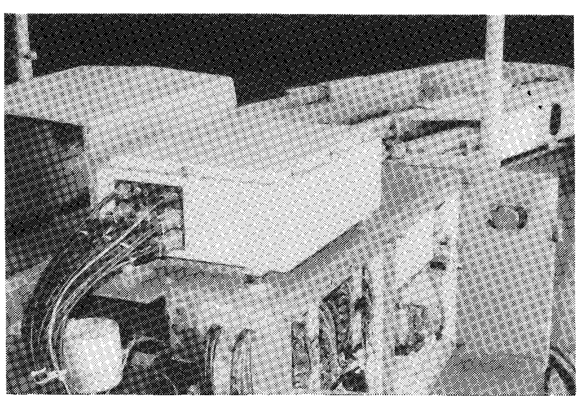

Figure 3.—Motor Monitoring System on continuous miner.

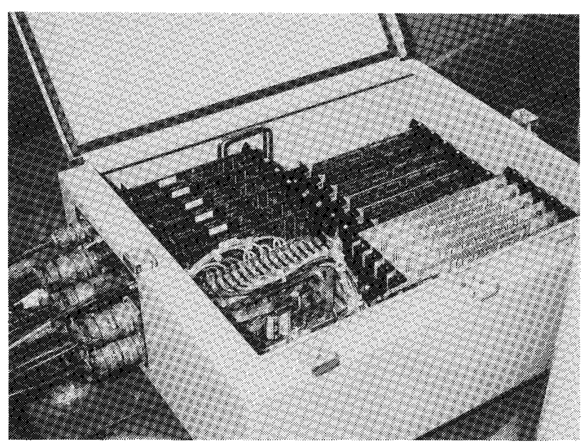

Figure 4.—Motor Monitoring System.

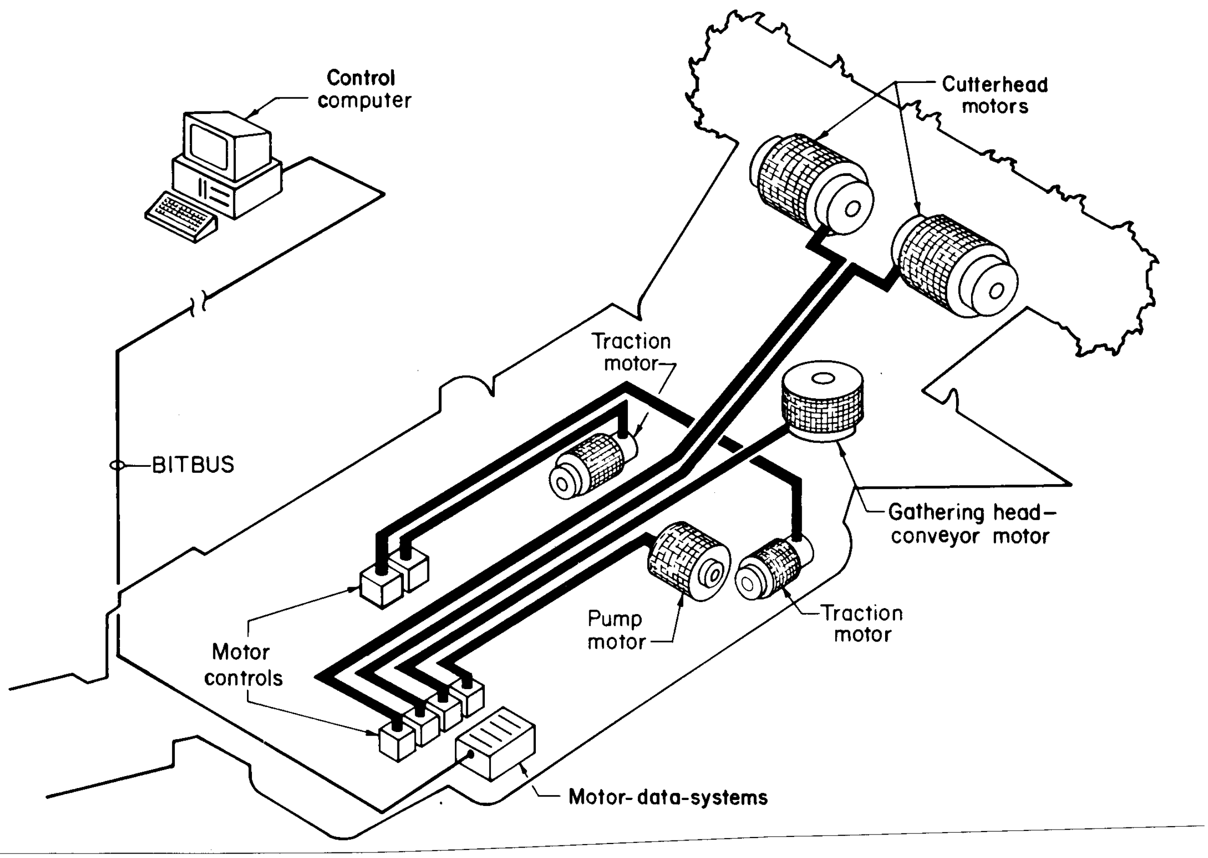

Figure 5.—Continuous miner, motors, controls, and Motor Monitoring System.

When this system was designed there were three options for transferring data between the motor-data-system and the control computer. The first was to send the raw data points from the ADC, the second was to send phasors, and the third was to calculate each motor's deterioration levels at the motor-data-system and send only the two deterioration values. However, when this system was considered as a part of a larger common BITBUS system that includes navigation and machine control systems, only the second method was viable. The first method overloads the bus and the third method does not provide phasor values for other nodes on the system that may need them.

ANALOG INTERFACE

The analog interface provides an interface between the current and potential transformers and the ADC on the single-board computers. Figure 6 shows the current and potential transformer wiring. There are current transformers for the line current on each phase of each motor and one set of potential transformers for the machine line-to-line voltages. The voltage signals are fed to each motor's analog interface since they are needed in calculating voltage and current phasor values with the proper phase relationship.

Figure 7 shows one of the analog interface boards that were designed and built in-house. Each board has seven channels, six of which are used by this system. Figure 8 shows a schematic wiring diagram of one channel. Each channel accepts a differential voltage signal of approximately 5 V peak-to-peak and outputs a 0- to 5-V signal centered at 2.50 V. This voltage offset is necessary because of the 0- to 5-V ADC's on the single-board computers.

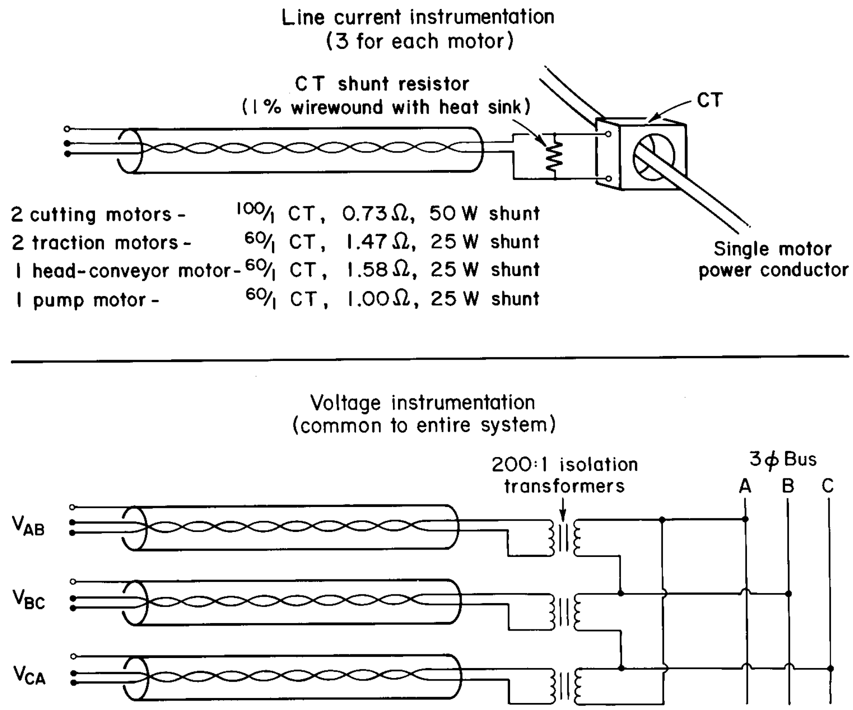

Figure 6.—Potential transformer and current transformer (CT) wiring.

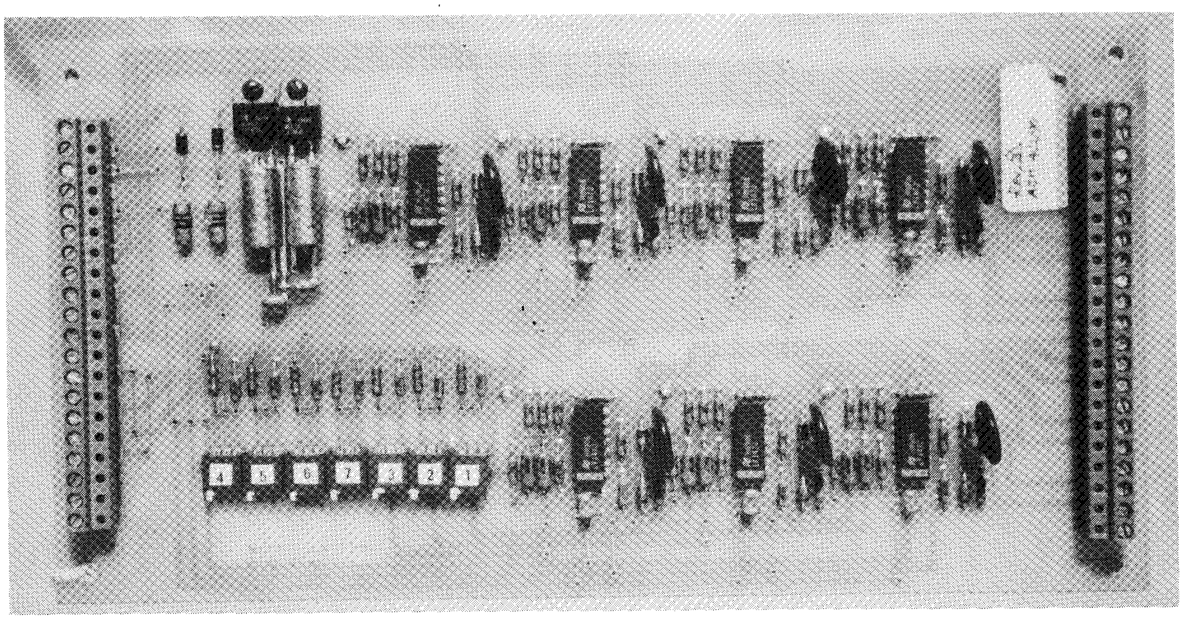

Figure 7.—Analog interface board.

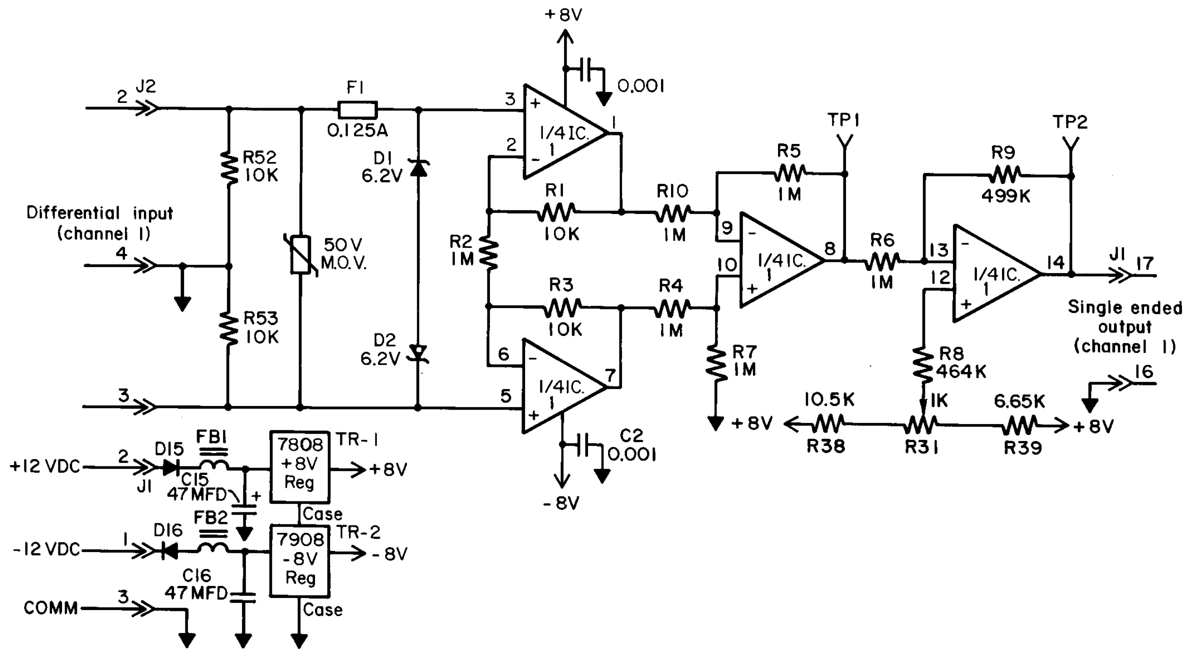

Figure 8.—Analog interface schematic for one channel.

BUS NODES

The bus nodes are Intel iRCB 44/10A digital input-output (I/O) controller boards. They are used to interface the motor-data-system with BITBUS. Figure 9 shows the parallel interface between a single-board computer and its bus node. The Start Data Acquisition bit is set on the bus node to start data acquisition and calculation of the phasors. When phasor calculation is done, the first byte of phasor data is stored in the data port and the Data Ready bit is set. This byte of data is read from the bus node data port, and the Data Request bit is set. All of the phasor data are sent to the control computer a byte at a time using the same process as for the first byte.

Some thought was given to combining the functions of a bus node and single-board computer by using an Intel iRCB 44/20 analog I/O remote control board. This idea was rejected because the board's operating system and ADC could not operate at the speeds and timing accuracy necessary to sample the voltage and current at 32 samples per cycle (11,520 samples per second). Also, the bus node 8051 microcontroller is not intended to be used for floating point calculations.

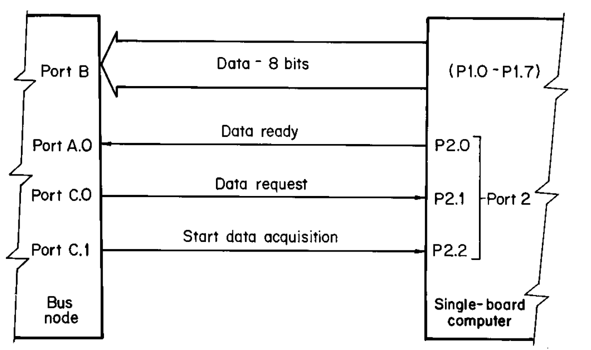

Figure 9.—Data and control signals between bus node and motor monitor.

SINGLE-BOARD COMPUTERS

The single-board computers are Intel 80C196KB microcontroller single-board computers (Intel EV80C196KB evaluation board). The 80C196KB microcontroller was chosen because it has an 8-channel 10-bit ADC, parallel ports and support for floating point operation, and because it is inexpensive.

SOFTWARE DESCRIPTION

There are two versions of the MMS program. The first uses character-oriented output, and the second uses graphic output. The first version was written using the programming languages C, Pascal, and PLM; the second was written entirely in C. This change took place because modules written in three languages were cumbersome to link. The first version was written using a data base written in-house. For the second version an off-the-shelf data base product was used.

Code also was written for the single-board computers. This code was written, compiled, and linked using a cross-assembler and then loaded into programmable read-only memory (PROM) for use in the single-board computers.

VERSION 1.0

Version 1.0 of the MMS program is a real-time, multitasking program that runs on the control computer. The program computes and displays motor deterioration values and services user menu requests while it collects motor data over the BITBUS network.

The MMS program was written mostly in Intel Pascal (PAS86 version 2.0) and Intel C (ic86 version 4.1), with a small piece of code written in Intel PLM86. Intel languages were chosen because of the need to use Intel's Universal BITBUS Interface (UBI) library, which is not compatible with other vendor languages. . Use of this library was necessary to communicate and perform remote access and control functions over the BITBUS network.

Initially, all programming was done in Pascal. Pascal code is generally considered to be very readable, making it easier to maintain. In addition, Bureau programmers had used Pascal extensively in previous programming efforts. These advantages, however, were quickly offset by some serious programming limitations placed on the language by the operating system.

Eventually, Bureau programmers decided to develop only C-coded program modules to avoid the problems encountered with Pascal. Although programs written in C can be quite cryptic and difficult to read, they are portable across different computer systems.

The MMS program was targeted to run on an IBM compatible PC with an operating system with real-time, multitasking capability. These operating system features were necessary for the MMS program to collect data over the network without interruption while servicing user menu requests and updating display information. The operating system (Microsoft Disk Operating System; MS-DOS) found on most PC's did not satisfy these requirements.

KADAK AMX-86 version 2.0 is a development package for configuring and implementing real-time, multitasking operating systems; AMX was found to be ideal for building the Bureau's MMS program. The programmer builds an application program, such as the MMS program, to use the various AMX facilities that enable real-time, multitasking programming. In addition, the programmer describes specific characteristics of the program in a configuration module for use by AMX during program execution. AMX uses this information to drive the program according to the programmer's specifications.

The primary objectives in writing the MMS program were to quantify motor deterioration and to activate a system alarm when the deterioration level rises above an acceptable threshold. To accomplish this objective, the program periodically collects data and applies formulas derived from laboratory investigations of motor winding insulation failure to compute deterioration levels. If the computed deterioration is out of range, an alarm is triggered.

A rudimentary data base was written to manage the motor data. Each time motor deterioration levels are computed and displayed they are subsequently written to a file on the hard disk. This output file is given the name of the current calendar date. All data collected on the same day are written to the same file. For example, all motor deterioration data collected on January 1, 1990, append to the daily file JAN0190.

Up to seven daily files are maintained by the MMS program. When attempts are made to open and write an eighth file, the oldest file's data are summarized and added to the summary data base, and that daily file is deleted.

Figure 10 shows the various functions available from the user menu. The user menu is divided into two tiers;

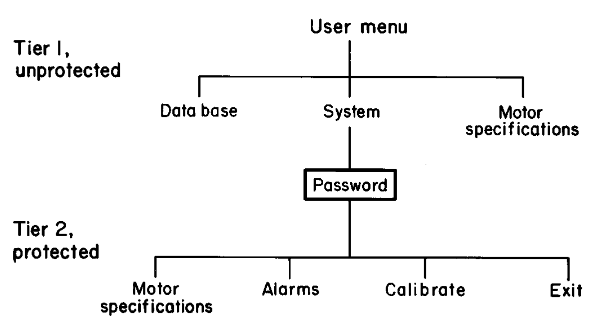

Figure 10.—Motor Monitoring System version 1.0 software command hierarchy.

tier 2 is protected by a password, and tier 1 is not. Password protection prevents unauthorized users from accessing functions that have a direct effect on system performance. For example, the calibrate and motor specification functions alter data used in computing motor deterioration.

Tier 1 (unprotected) menu options are as follows:

Data base.—Allows a user to examine the contents of the historical data base file or any one of the daily files.

Motor specifications.—Allows a user to read the specification listing on any motor.

System.—Provides access to protected menu functions. The user must know the system password to proceed from this menu option to the tier 2 options listed below.

Tier 2 (protected) menu options are as follows:

Motor specifications.—Permits a user to edit motor specification data. This option is typically chosen after an existing motor is replaced by one with different specifications. Since motor specification data are used in calculating deterioration, it is essential that this information be kept up to date.

Alarms.—Allows a user to activate or disable the MMS alarm for any motor.

Calibrate.—Allows a user to calculate a new software calibration factor for a motor. Calibration factors are typically computed once, either when the MMS program is installed for the first time or when a motor is replaced.

Exit.—Allows the user to terminate the MMS program.

Version 1.0 of the MMS program accomplished all stated design objectives and was subsequently installed on the Joy 16CM continuous miner for demonstration purposes. However, like most first-version programming efforts, the program evolved over time and this caused problems, specifically two key problems. First and most notable was the fact that the program lacked modularity (because of the cut-and-paste nature of writing the program as time went on). This made it difficult to incorporate new features. Second, the program was written in three languages. Although the languages are Intel products, they are implemented differently.

VERSION 2.0

After using Version 1.0, it became evident that a second version was needed. Although Version 1.0 met the original design objectives, several features needed to be changed to improve program performance and usage.

Version 2.0 is a demonstration program rather than a prototype of a program that can be used in the field. Graphics mode is used to display user information more clearly. Although actual data are taken and displayed, these data are not used when trend lines are displayed, because the miner is not run frequently enough to get enough data from the miner to show meaningful trend lines. Data developed from Bureau experience in modeling motors were used to display trends.

Version 2.0 of the MMS is written entirely in Borland Turbo C version 2.0. A library of functions was developed to replace the Intel BITBUS library, which is not compatible with Turbo C.

Version 2.0 is made up of two programs rather than one as in Version 1.0. The first program (MMSP) is the actual demonstration program, and the second program (MMSXP) is used to set various system variables used by MMSP.

MMSP was programmed using KADAK AMX-86 version 3.0 as an operating system. MMSP is, however, a much simpler program than Version 1.0 because it operates mostly in non-real-time mode. Only the data acquisition and display update are done in real-time.

The program has two major displays. The first display shows the miner in outline with the motors shown symbolically in color. The color of each motor symbol, green, yellow, or red, indicates the relative state of each motor based on its most recent deterioration values. Green represents a motor with normal deterioration values, yellow represents higher-than-normal values, and red represents a motor with deterioration values high enough to indicate imminent failure. While in this display the user can also display one or more windows that show the deterioration values for all motors, the state of the audible alarm, and trend line graphs. The second display is a simulation of the display the machine operator would see—a red, yellow, or green light for each motor.

MMSXP is an auxiliary program used to set system variables used by MMSP. These variables are alarm levels, timer interval, and calibration constants. This program must be run at a time when MMSP is not running. MMSXP is a normal (non-real-time) program that was programmed using Turbo C version 2.0 and Vermont Views version 2.0 windowing software.

SINGLE-BOARD COMPUTER SOFTWARE

All programming for the single-board computers was done using the Intel ASM-96 assembler and the Intel relocator and linker, RL96, on an IBM AT clone. An in-circuit emulator (Intel ICE-196PC) running on the same IBM AT clone was used for debugging software. When the software was running properly it was transferred to PROM's and these PROM's were installed on the single-board computers.

Figure 11 is a flow diagram of the program. The program was written in three modules: A2DRUN, A2D, and FFTV5. A2DRUN is the main module that controls the flow of the program. A2D is a module that contains the code for the acquisition of data via the ADC. FFTV5 is a fast Fourier transform module (*6*) that is used to obtain the phasor values sent back to the control computer by way of the BITBUS. The flow of the program is fairly simple. The program first initializes its stack and the processor's parallel I/O ports. Then the program goes into a loop waiting for the Data Request bit (fig. 9) to be set. When this is done the program acquires the data using code from the A2D module and calculates phasor data using the FFTV5 module. After the data are calculated, they are sent to the control computer a byte at a time by way of BITBUS.

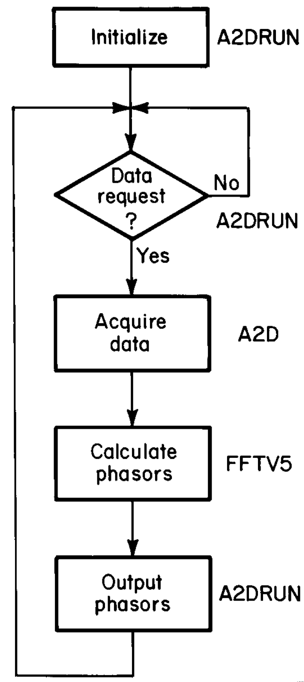

Figure 11.—Single-board computer program flow diagram.

ANTICIPATED FUTURE DEVELOPMENT

ALN's have been developed for four motor sizes: 10, 50, 100, and 150 hp. The MMS uses the 50-hp ALN, which provides acceptable results, even though the motors range from 15 to 175 hp. Future systems would either calculate deterioration using an ALN for each motor that closely matches that motor, or a single ALN for a range of motors that approximate the miner's motors.

MMS's used in mines would take a different form from the system described above. The system would consist of a motor-data-system for each motor but without a control computer. The motor-data-system would calculate and temporarily store the deterioration values for its motor. If a deterioration value were to go out of range the motor-data-system would send a message to the operator's panel indicating that the motor is about to fail. Periodically the motor-data-systems would send the stored data to a computer in the mine office over a data link or to a portable computer that could be brought to the machine. When transferred, the data would be added to a data base of deterioration values for each motor. These data could then be studied to better estimate the time to failure for any motor.

SUMMARY

An MMS was developed for use on a continuous miner. Two versions of the system were developed; they differ only in the control computer software. Version 1.0 uses character-based output, and Version 2.0 uses graphics output. Version 2.0 also uses a separate program to set system operating parameters rather than including these functions in the main program.

If a future system is developed it would likely reside entirely on the miner with only a very basic operator display. In this case, a method would be needed to transfer deterioration values from the system to a computer in the mine office. The mine office computer could then be used to track trends in the deterioration values. In addition, separate ALN's would be used for each motor, or one common ALN would be developed specifically for the miner's motors.

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